Advanced Nuclear Systems for Sustainable and Environmentally Acceptable Energy

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Abstract

Energy is critical to human development and central to the challenge of sustainability in the social, economic, and environmental needs. With the growth of world population and rapid increase in energy demand to meet human development needs, it is essential to ensure energy sources that are environmentally clean and economically attractive. Nuclear energy is by far the largest source of carbon-emission-free electricity production. It can provide a reliable, environmentally friendly, large-scale source of base load electric-generating capacity with the potential utilization for high-temperature hydrogen production and water desalination. Public perceptions about nuclear power have been mostly negative because of concerns about safety, waste disposal, nuclear weapons proliferation, high upfront capital cost, and long construction time. Such concerns must be resolved if nuclear technology is to play a prominent role in the transition to a sustainable global energy mix. To alleviate these concerns, significant effort is underway to develop new generations of advanced nuclear reactors as well as innovative approaches to utilizing nuclear energy. We will review the advanced generation III and generation IV reactor designs as well as the most recent Global Nuclear Energy Partnership (GNEP) R&D activities that involve development of advanced proliferation-resistant fuel recycling technologies as well as advanced burner reactors to reduce the radioactive waste inventory. Nuclear fusion energy, with nearly inexhaustible fuel resources, can play a major role in satisfying global energy demand in the long term. The status of its development will also be addressed.

I. Introduction

Energy is critical to human development and is central to the challenge of sustainability in the social, economic, and environmental needs. Currently, about one-third of the world population has no access to electricity and still another third has only limited access. In the next 50 years, as world population expands, today's vast unmet human needs could multiply severely. Over the 20th century alone, the world population grew 3.8 times, from 1.6 to 6.1 billion people and the annual worldwide primary energy use rose ten-fold [1]. Current projections suggest that the world's population will grow by another 50 percent over the first half of this century (to approximately 9 billion by 2050) and global energy consumption will double [1].

Fossil fuels (coal, oil, and natural gas) account for ~80% of the world primary energy consumption with the rest contributed by nuclear, hydropower, and renewable resources (biomass, wind, and solar power) [1]. Fossil-fuel combustion is responsible for substantial emissions of air pollutants and currently accounts for well over half of the total greenhouse gas emissions that lead to enhanced global warming. The concentration of carbon dioxide has increased significantly in the past 50 years as shown in Figure 1 [2]. In order to reduce climate-change risks and preserve the environment for future generations it is essential to make the transition to lower-carbon energy options. A continuation of business-as-usual trends will produce a roughly 55 percent increase in carbon dioxide emissions over the next two decades. At the present consumption rate, oil, natural gas, and coal proven reserves will last for 40, 60, and 140 years, respectively [3]. The total amount of resources could increase as more unconventional improved extraction capabilities are developed. This could extend lifetime of fossil fuel resources by a factor of 5-10 but extraction will involve advanced technologies, higher costs, and possibly serious environmental problems [3].

Apart from hydro power in the few places where it is very plentiful, none of the renewable energy sources for electricity is suitable, intrinsically or economically, for large-scale power generation where continuous, reliable supply is needed. The International Energy Agency projects that, even with continued subsidy and research support, the new renewables (solar, wind, biomass and geothermal power) can only provide around 6% of world electricity by 2030 [4]. Renewables will have most appeal where demand is for small-scale, intermittent supply of electricity. We would still need large-scale source of around-the-clock electricity to meet much of our energy needs. Nuclear energy is the only proven option with the capacity to produce vastly expanded supplies of clean electricity on a global scale. In the United States, it contributes ~70% of the emission-free electricity production as shown in Figure 2 [5].

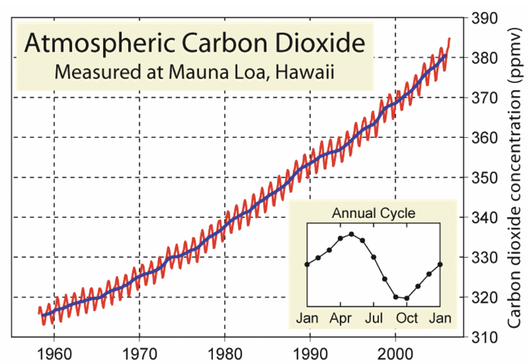

Figure 1: Recent Increase in Atmospheric Carbon Dioxide.

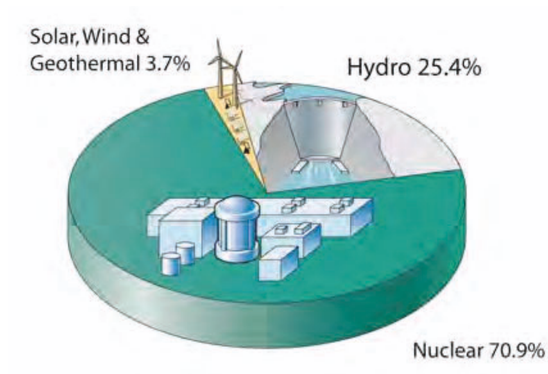

Figure 2: Contribution to the emission-free electricity production in the United States

Nuclear power supplies ~16% of today's global electricity demand with 439 nuclear power reactors in 30 countries that produce a combined capacity of 372 GW. There are presently 30 new reactors under construction in 13 countries [6]. Nuclear power can provide a reliable, environmentally friendly, large-scale source of base load electric-generating capacity with the potential utilization for high-temperature hydrogen production and water desalination. In the presence of binding carbon-emission reduction constraints and with rising fossil fuel prices the economics of nuclear power could become favorable in many countries. Public perceptions about nuclear power have been mostly negative because of concerns about safety, waste disposal, nuclear weapons proliferation, high upfront capital cost, and long construction time [7]. Such concerns must be resolved if nuclear technology is to play a prominent role in the transition to a sustainable global energy mix. Accidents at Three Mile Island in 1979 and Chernobyl in 1986 have had a long-lasting effect on public perceptions of nuclear power. Developments on several fronts since the 1979 TMI accident have resulted in considerably improved safety. Fuel reprocessing and recycling could significantly reduce the amount of high-level waste that needs deep geological burial. Increased international collaboration is needed to explore options for addressing enrichment and reprocessing needs in ways that minimize public safety and proliferation risks. A further concern in many countries relates to the need for significant amounts of capital and considerable institutional capacity and technical expertise to successfully build and safely operate nuclear power plants. It is essential to have independent autonomous regulatory agencies to ensure that required regulations are strictly implemented during construction and operation. Development of simplified, standardized reactor designs that would expedite licensing and construction will greatly improve the economical attractiveness of nuclear power. Significant effort took place to alleviate the concerns with nuclear power by developing new generations of advanced nuclear reactors as will as innovative approaches to utilizing nuclear energy. In this paper we review these advanced and innovative Systems.

II. Generations of Nuclear Power

Figure 3 shows the evolution of nuclear power reactors in the past 50 years. Generation I (GEN I) reactors were developed in 1950-60s and the only GEN I reactors still in operation are six small (<250 MW_e) gas-cooled plants in the United Kingdom. Most reactors operating today are Generation II (GEN II) reactors designed in the late 1960s and 1970s. These reactors have achieved very high operational reliability, mainly through continuous improvement of their operations. GEN II reactors use ceramic fuel instead of the metallic fuel used in GEN I. Generation III (GEN III) reactors are advanced reactors that represent an evolution from the GEN II reactors with improved fuel technology, passive safety systems, and standardized design. GEN III reactors have been operating since 1996 and advanced late 3rd generation (GEN III+) designs are now being built [8]. Generation IV (GEN IV) reactors are revolutionary designs under development that improve safety, economics and proliferation resistance, minimize waste, and increase fuel utilization [9]. GEN IV reactors are to be deployed no later than 2030.

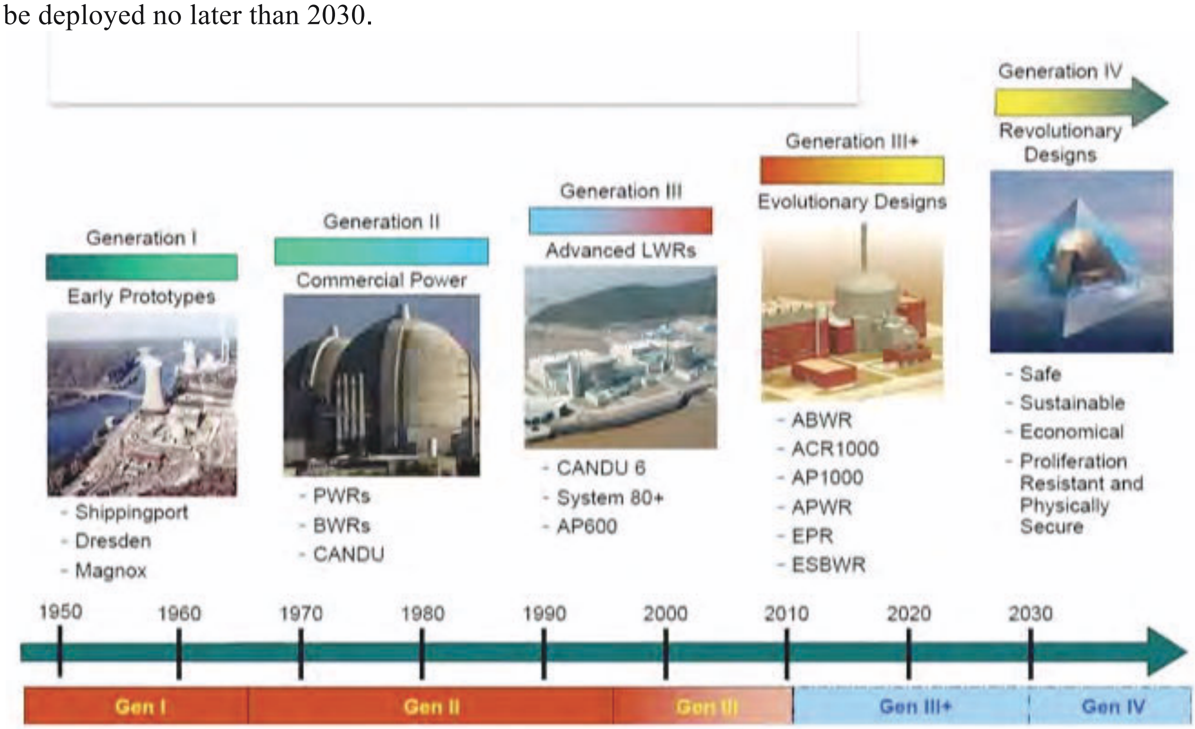

Figure 3. Generations of nuclear power

III. Generation III Nuclear Power Reactors

The greatest improvement in these reactors is that they incorporate passive or inherent safety features that require no active controls or operational intervention to avoid accidents in the event of malfunction [8]. They may rely on gravity with the chance of core meltdown being nearly impossible in the event of an accident even with a total loss of operation of the reactor control systems. There is a standardized design for each concept to expedite licensing, reduce capital cost and reduce construction time. They have higher availability and longer operating life of ~60 years. Most of them have higher burn-up resulting in better fuel utilization and waste reduction. GEN III reactors were designed in the 1990s, and several of them have been built in France and Japan. More recent designs are labeled GEN III+ reactors and are likely to be constructed in the coming years.

Examples of advanced GEN III light water reactors (ALWR) are the advanced boiling water reactor (ABWR), the System 80+, and the AP600. Two ABWRs have been operating in Japan since 1996, and more are under construction. Using Internal recirculation pumps inside of the reactor pressure vessel is a major improvement over previous GEN II BWRs. The System 80+ is a 1300 MWe advanced pressurized water reactor with a reactor coolant system that has a two loop configuration. The System 80+ has provided the basis for the APR1400 that has been developed in Korea for future deployment with enhanced safety and seismic robustness. The Evolutionary Power Reactor (EPR) is a PWR with simplified components and enhanced reactor safety. It employs four independent emergency cooling systems, each capable of cooling down the reactor after shutdown. The AP600 is an advanced PWR design that has innovative passive safety features resulting in a greatly simplified reactor design. The AP1000 with a much simplified design that is intended to cut the material and construction costs of the plant has 50% fewer valves, 83% less piping, 87% less control cables, 35% fewer pumps and 50% less seismic building volume than a similarly sized GEN II PWR.

The Economic Simplified Boiling Water Reactor (ESBWR) is a passively safe GEN III+ reactor that builds on the success of the ABWR. The intent of the new design, which includes new passive safety features, is to cut construction and operating costs significantly from the ABWR design. The ESBWR uses natural circulation with no recirculation pumps or their associated piping. The SWR-1000 ("Siedewasser Reaktor") is a Framatome ANP design for an advanced BWR. Several other advanced LWRs are being developed worldwide. The Mitsubishi's large advanced PWR (APWR) was developed in collaboration with four utilities and will be the basis for the next generation of Japanese PWRs. In Russia, several advanced PWR designs have been developed with passive safety features. Examples are VVER-1000 units that are being built in India, China, and Bulgaria.

The Atomic Energy of Canada Limited (AECL) offers the "Advanced CANDU Reactors" ACR-700 and ACR-1000 which have been developed as an evolution from AECL's internationally successful CANDU line of PHWRs. One of the innovations, compared to earlier CANDU designs, is that heavy water is used only as a moderator while light water is used as the coolant. Adopting light water cooling and a more compact core reduces capital cost, and because the coolant runs at higher temperature and pressure, it has higher thermal efficiency. India is developing the Advanced Heavy Water reactor (AHWR) that aims at utilizing the thorium fuel cycle for commercial power generation. The Pebble-bed Modular Reactor (PBMR), which uses helium gas for heat transfer, is part of the high temperature gas cooled reactor (HTGR) family of reactors and thus a product of a lengthy history of research. At around 165 MWe the PBMR is one of the smallest reactors now being proposed for the market with less capital investments than larger new units. They have a direct-cycle gas turbine generator with helium temperature up to 950°C and thermal efficiency ~42%. On-line refueling gives high capacity factors.

IV. GEN IV Nuclear Systems

The GEN IV International Forum (GIF) was initiated in 2000 by ten countries (Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, Switzerland, the United Kingdom, and the United States) with the International Atomic Energy Agency, and the OECD Nuclear Energy Agency as permanent observers. to investigate innovative nuclear energy system concepts for meeting future energy challenges [9]. The GIF members commit to joint development of the next generation of nuclear technology for deployment between 2020 and 2030. GEN IV is widely recognized as an R&D program for reactors with advanced features well beyond the GEN III+. The primary goals for GEN IV development are to improve nuclear safety, improve proliferation resistance, minimize waste and natural resource utilization, and to decrease the cost to build and run such plants. In 2002, the GIF announced the selection of six reactor technologies that could achieve these goals [10]. These most promising systems are the very high temperature gas reactor (VHTR), the super-critical water reactor (SCWR), the lead-cooled fast reactor (LFR), the sodium-cooled fast reactor (SFR), the gas-cooled fast reactor (GFR), and the molten salt reactor (MSR). All of these operate at higher temperatures (510-1000°C) than today's LWRs allowing for higher efficiencies with four being able to support hydrogen production. Most of the systems (except the VHTR) employ a closed fuel cycle to maximize the resource base and minimize high-level wastes sent to a repository. Only one, SCWR, is cooled by light water, two are helium-cooled and the others have lead-bismuth, sodium or fluoride salt coolant.

The latter three operate at low pressure, with significant safety advantage. Detailed description of the features of these six GEN IV concepts is provided in Ref. 10. There are many challenges, specific to each concept, that need to be addressed by aggressive R&D program before the GEN IV concepts can be deployed.

V. The Global Nuclear Energy Partnership

The Global Nuclear Energy Partnership (GNEP), announced by the United States in 2006, is a plan to enable the global expansion of nuclear energy for peaceful purposes, while reducing proliferation concerns, to help meet growing energy demand in an environmentally sustainable manner and make a major contribution to global development into the 21st century [11]. Through GNEP, new proliferation-resistant recycling technologies will be developed in order to produce more energy, reduce waste, and minimize proliferation concerns. The GNEP program has several elements. It will develop, demonstrate, and deploy advanced technologies for recycling spent nuclear fuel, centered in existing fuel-cycle states, that do not separate plutonium, with the goal over time of ceasing separation of plutonium, reducing or eliminating excess stocks of civilian plutonium, and drawing down existing stocks of civilian spent fuel. Such advanced fuel cycle technologies would substantially reduce nuclear waste, and simplify its disposition. The most significant repository benefits can be achieved by removing the very long-lived minor actinides and recycling them as part of the fuel for Advanced Burner Reactors (ABR). These are fast reactors that use the actinide based fuel to burn the actinides and produce electricity. A schematic of the GNEP fuel cycle is shown in Figure 4.

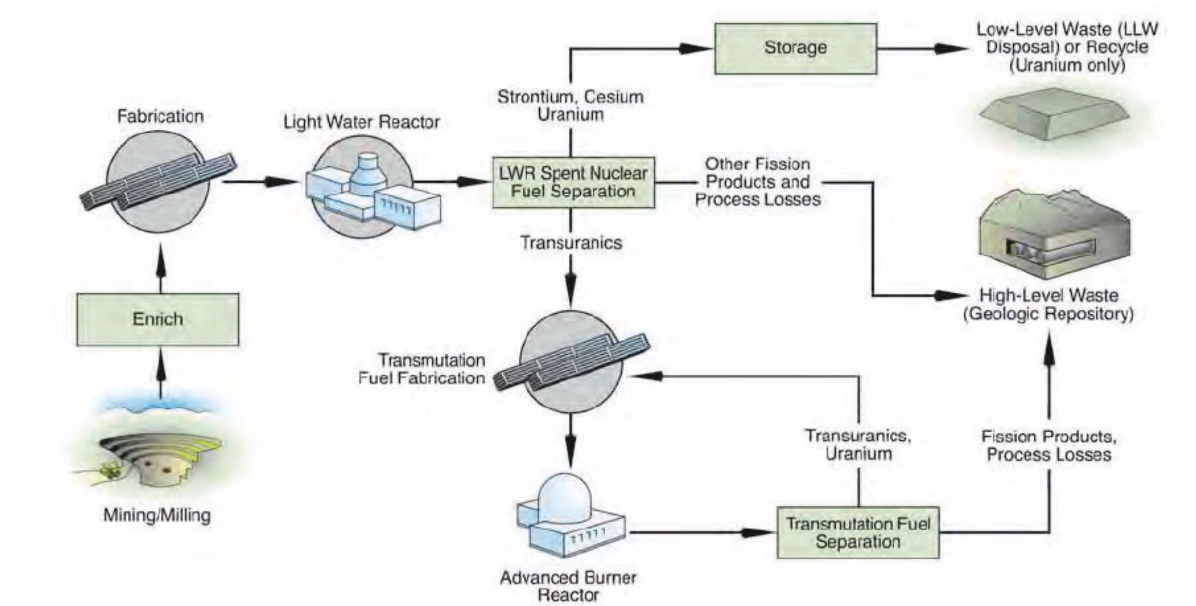

Figure 4. GNEP fuel cycle

An international fuel service is an essential part of reducing proliferation risk. GNEP will establish supply arrangements among nations to provide reliable fuel services worldwide for generating nuclear energy by providing nuclear fuel and taking back spent fuel for recycling without spreading enrichment and reprocessing technologies. This provides nuclear fuel to developing nations in exchange for their commitment to forgo enrichment and reprocessing activities. A group of fuel supplier countries operates reactors and fuel cycle facilities, including fast reactors to transmute the actinides from spent fuel. Fuel User countries will operate reactors and lease and return fuel. GNEP will develop, demonstrate, and deploy advanced, proliferation-resistant nuclear power reactors appropriate for the power grids of developing countries and regions. The IAEA role is to provide safeguards and fuel assurances, backed up with a reserve of nuclear fuel for states that do not pursue enrichment and reprocessing. Technical challenges remain for the implementation of the closed-fuel cycle as envisioned under GNEP. Many of the technologies essential for the successful implementation of GNEP have been demonstrated at laboratory and bench scale. But uncertainties, such as scaling-up the chemical separations for the recycle process or fabricating and qualifying the transmutation fuel for the advanced burner reactor, exist and require careful attention. These technical risks will be addressed by continued R&D and technology development for GNEP.

The GNEP vision has been well received by the international nuclear community, particularly among the leading fuel-cycle states. On February 16, 2006 the U.S., Russia, China, France and Japan signed an "arrangement" to research and develop sodium-cooled fast reactors in support of the GNEP. On September 16, 2007, 11 more countries signed into GNEP, bringing the number of GNEP participants to 16. These 11 countries were Australia, Bulgaria, Ghana, Hungary, Jordan, Kazakhstan, Lithuania, Poland, Romania, Slovenia, and Ukraine. Since then 9 additional countries (Armenia, Canada, Estonia, Italy, Republic of Korea, Morocco, Oman, Senegal, and United Kingdom) have joined. The 25 GNEP members agreed to set up a nuclear fuel services working group, to address nuclear fuel leasing and other considerations around comprehensive nuclear fuel supply goals. Another working group, on nuclear infrastructure development, would address the financial, technical and manpower challenges surrounding nuclear power deployment in many countries [11].

VI. Nuclear Fusion Energy

Unlike fission, fusion occurs when two hydrogen nuclei fuse together and release energy. The most promising nuclear reaction for fusion power generation is the D-T reaction. Energetic 14 MeV neutrons are emitted in the fuel (plasma) and slowed down and absorbed by surrounding components. While deuterium is naturally occurring, a fusion power reactor should produce enough tritium, by absorbing neutrons in lithium, to compensate for that burned. Fusion energy represents a nearly inexhaustible source of energy with vast quantities of the primary fuels, deuterium and lithium (from which tritium is produced), being available. A blanket that contains lithium-bearing material recovers thermal power and produce needed tritium. Other components around the plasma include a vacuum vessel, and a radiation shield. Two approaches are used for plasma confinement. These are magnetic confinement achieved by a set of superconducting magnets outside the vacuum vessel and inertial confinement where a small DT target is compressed and ignited upon bombardment by intense laser beams.

Fusion systems have safety advantage over fission systems. The fusion reaction in the plasma will cease rapidly following any abnormal conditions and meltdown of a fusion system is not possible. Unlike fission systems where most of the radioactive waste is generated in the fuel itself, the radioactive waste in fusion systems is generated in materials surrounding the fuel (plasma) as a result of neutron interactions. Careful choice of “low activation” materials results in significant reduction of the amount of long-lived radioactive waste. Most fusion waste can be either recycled or is classified as low-level waste for shallow land burial. Many technology and physics challenges remain to be addressed before realizing commercial power production from fusion systems. A major step in this direction is the ITER fusion test reactor [12]. ITER shown in Figure 5 is intended to be an experimental step between today's studies of plasma physics and future fusion power plants. It is being built in Cadarache, France with participation from the European Union, Russia, Japan, Korea, India, China, and the US. Construction started in 2008 and the first plasma operation is expected in 2018. It is predicted that commercial fusion power plants will be available in the middle of the 21st century.

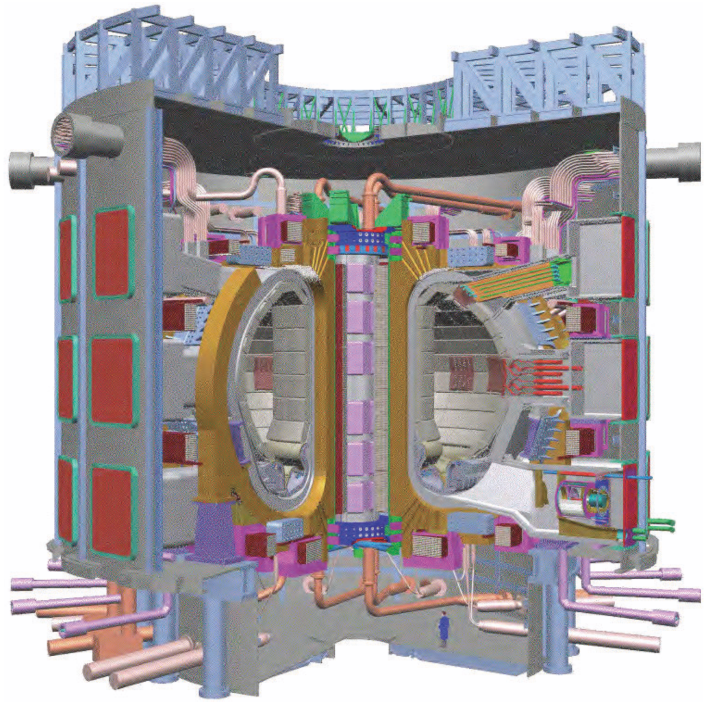

Figure 12. ITER fusion test reactor

VII. Conclusions

With the growth of world population and rapid increase in energy demand to meet human development needs, it is essential to ensure energy sources for the 21st century and beyond that are environmentally clean and economically attractive. Nuclear energy is by far the largest source of carbon-emission-free electricity production. To alleviate concerns about safety, waste disposal, nuclear weapon proliferation, high capital cost, and long construction time, significant effort is underway to develop new generations of advanced nuclear reactors as well as innovative approaches to utilizing nuclear energy. GEN III reactors are advanced reactors that represent an evolution from today's GEN II reactors with improved fuel technology, passive safety systems, and standardized design. GEN IV reactors are revolutionary designs that improve safety, economics and proliferation resistance, minimize waste, and increase fuel utilization and are to be deployed no later than 2030. Six reactor technologies are being developed to achieve these goals. The Global Nuclear Energy Partnership (GNEP) aims at enabling the global expansion of nuclear energy for peaceful purposes, while reducing proliferation concerns, to help meet growing energy demand in an environmentally sustainable manner and make a major contribution to global development into the 21st century. Through GNEP, new proliferation-resistant recycling technologies will be developed in order to produce more energy, reduce waste, and minimize proliferation concerns. It also involves development of advanced burner reactors to reduce the radioactive waste inventory. Nuclear fusion energy with nearly inexhaustible fuel resources can play a major role in satisfying global energy demand in the long term.

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